Engineering Intuition for FIRST Robotics

WHEELER
CircuitRunners

What is Engineering Intuition?

- Math describes world around us
- You learn how exactly that works in engineering school. For now, it’s much more important to understand key principles

How can we use engineering principles to inform our designs?

We can figure out why something broke and how to not make it break next time

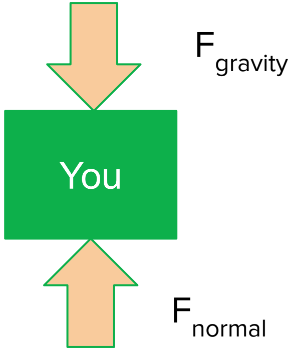
Forces & Moments

Basic Physics- Forces, Newton’s 2nd, and FBDs

- Tl;dr- forces move things in directions!
- But they are also present when things aren’t moving, like gravity acting on you when you’re in a chair… how can this be?

$$\sum F = ma$$

- Can use free body diagrams (FBDs) to describe you sitting still in a chair:

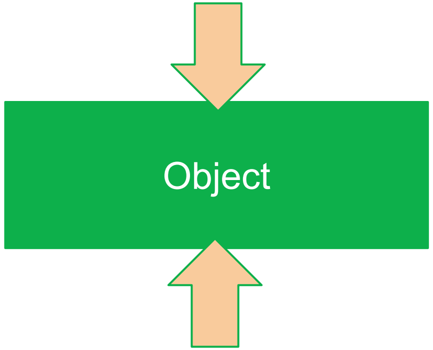


$$\sum F = F_{gravity} + F_{normal} = 0$$

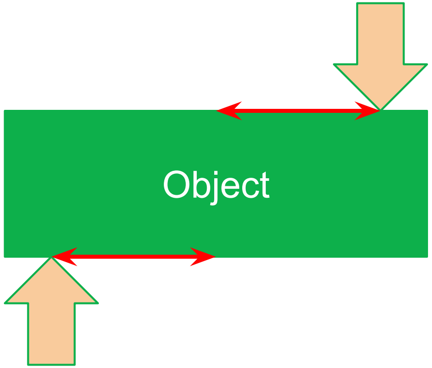
Basic Physics- Moments

- Also called torques… basically forces that aren't lined up can twist an object:

No Twist

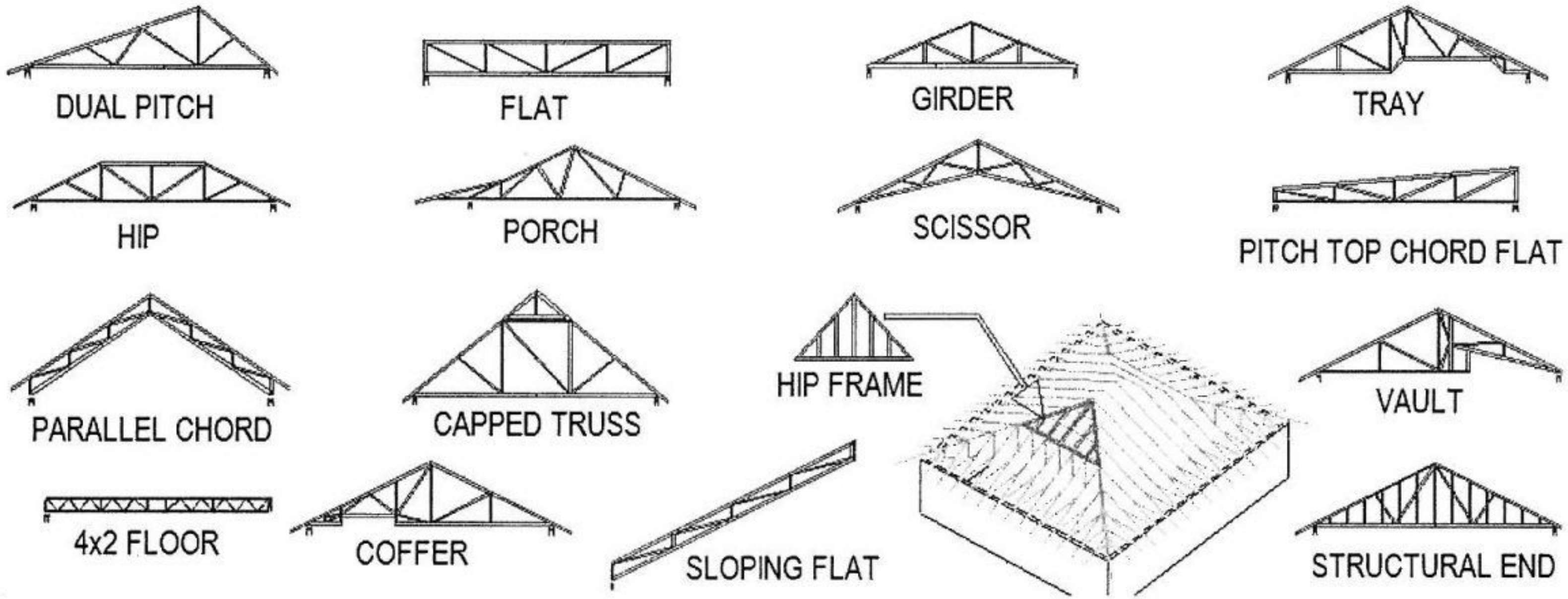


Twist



This is quantified through the relation:
Moment = Force x Distance from CoG

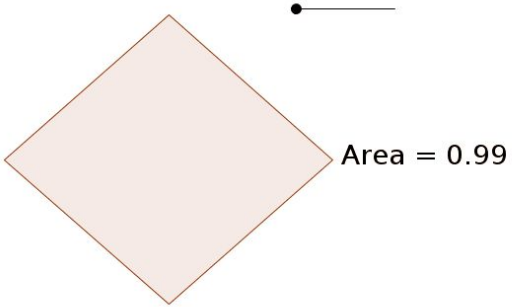
High Level Concepts



Find the similarities in these engineering trusses...

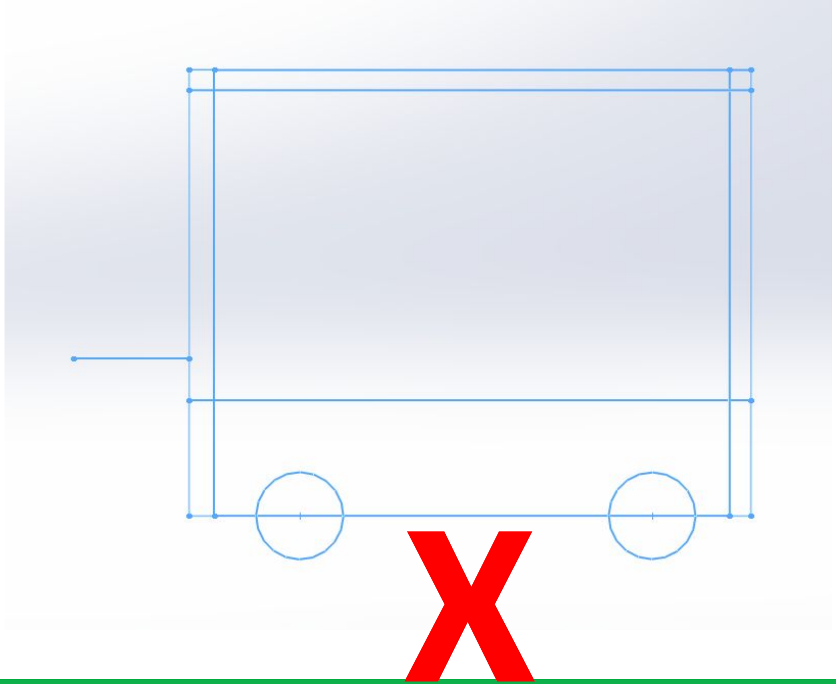
Triangles are OG

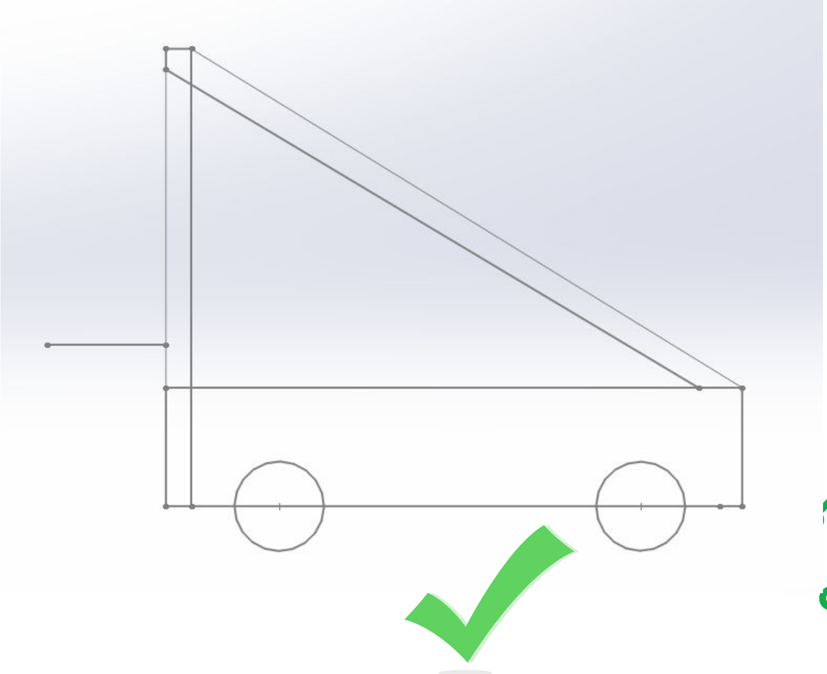
- Squares can change shape without changing a side length
- Triangles can’t! That makes them a really good engineering shape



Triangles are OG… in FIRST

- Say you want to build an elevator system… don't be silly, use triangles to support it!

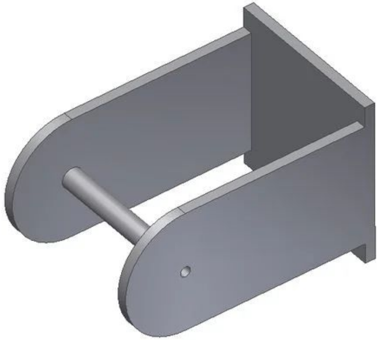


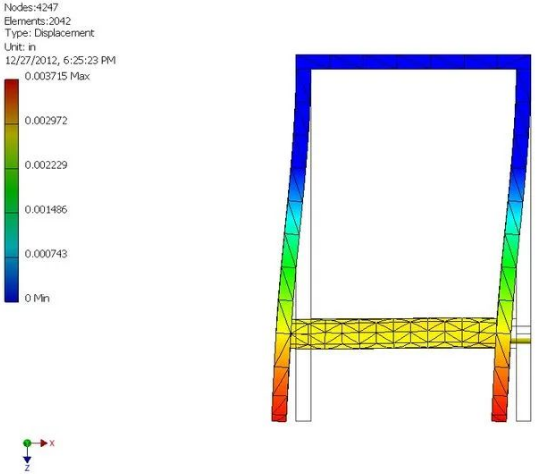


Other examples

Triangle Gussets...

Squares messing things up...

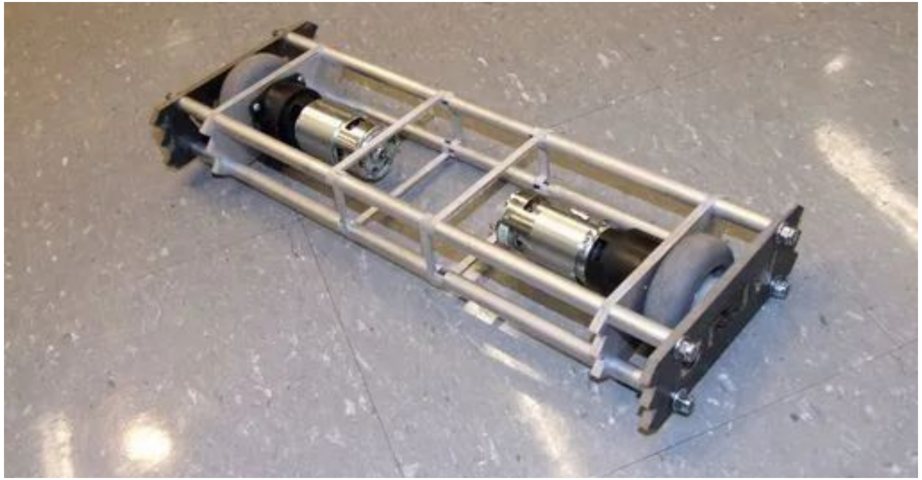




Making 3D things:

There are lots of ways to make 3D parts.. Here are some of our favorites

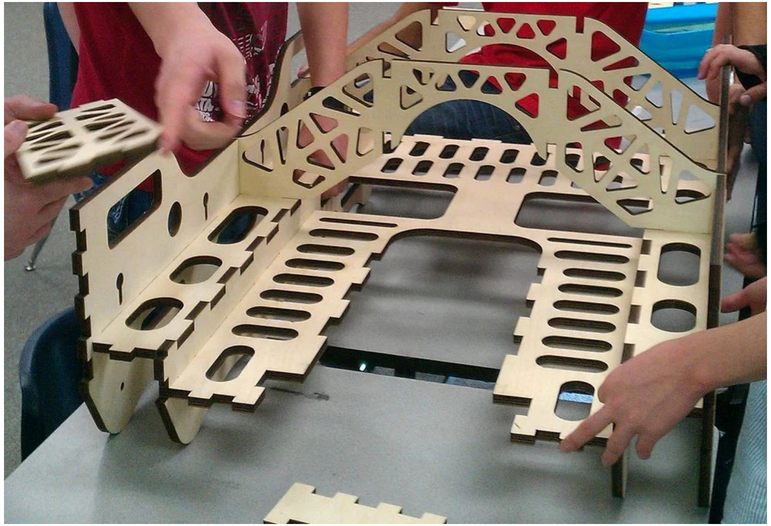
Sheet metal bend + rivets



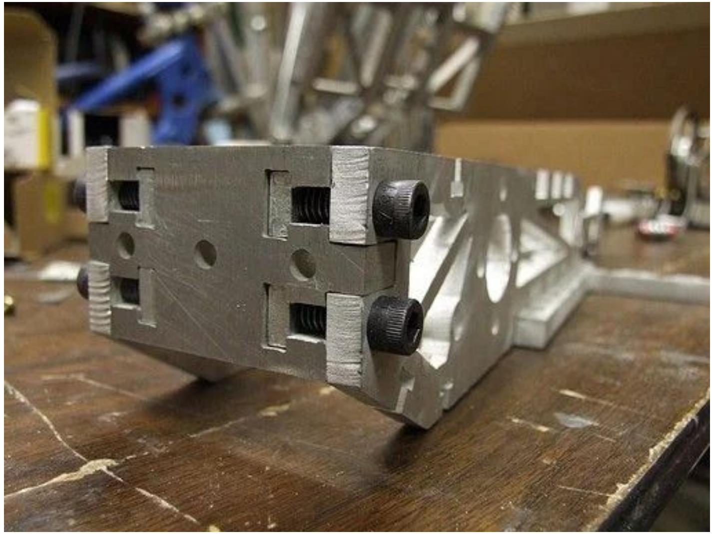
Standoffs between plates

Making 3D things:

Finger joints (and T-nut slots):



FRC 1771 robot



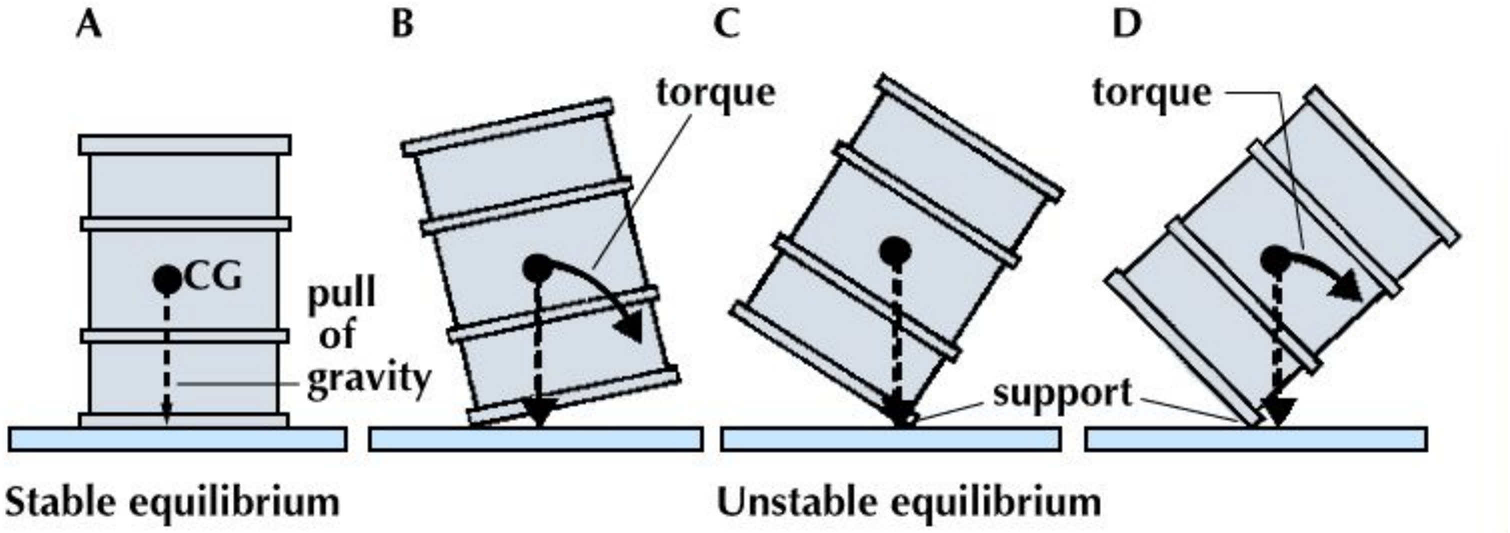
T-nuts in use

For more, check out

https://www.instructables.com/id/How-to-Build-your-Everything-Really-Really-Fast/

Center of Gravity

When designing robots that are tall.. Important to think about CoG!



The lower your COG is.. The harder it is for your robot to tip over

Material Selection

Important to choose what material you should use!

Plastics: Lower strength, but easier to work than metals (Ex. Delrin, Polycarb, PLA)

Metals: Higher strength, harder to work with (Ex. Aluminum 6061, Steel)

Ceramics: Very hard and brittle but strong, insulating (Ex. grinding wheels, high voltage electronics)

Wood: Easy to prototype with, can be strong if reinforced right (Ex. Plywood sheets for laser cutting)

Lots more goes into that.. Check out https://blog.thebluealliance.com/2018/12/27/crash-course-frc-materials-suppliers/

Simple Machines

What are some examples of simple machines?

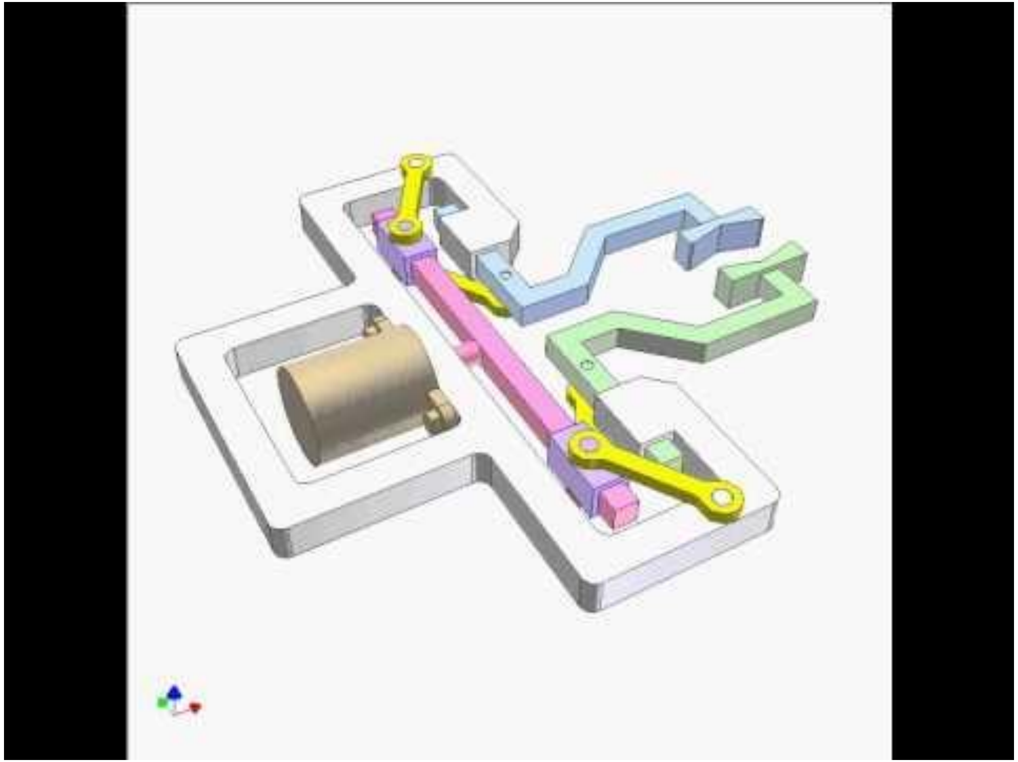
- Lever
- Wheel and axle
- Pulley
- Inclined plane
- Wedge
- Screw

All of these **take a force and modify its direction and/or magnitude**

Building on that… linkages / mechanisms

- Linkages use simple machines to do things!
- They convert rotational motion to linear motion and vise versa
- Very useful for FIRST applications if done right…
- Check out:
    - https://hackaday.com/2016/02/29/2100-mechanical-mechanisms/
    - http://507movements.com/
    - https://www.dmg-lib.org/

Linkage Design Example

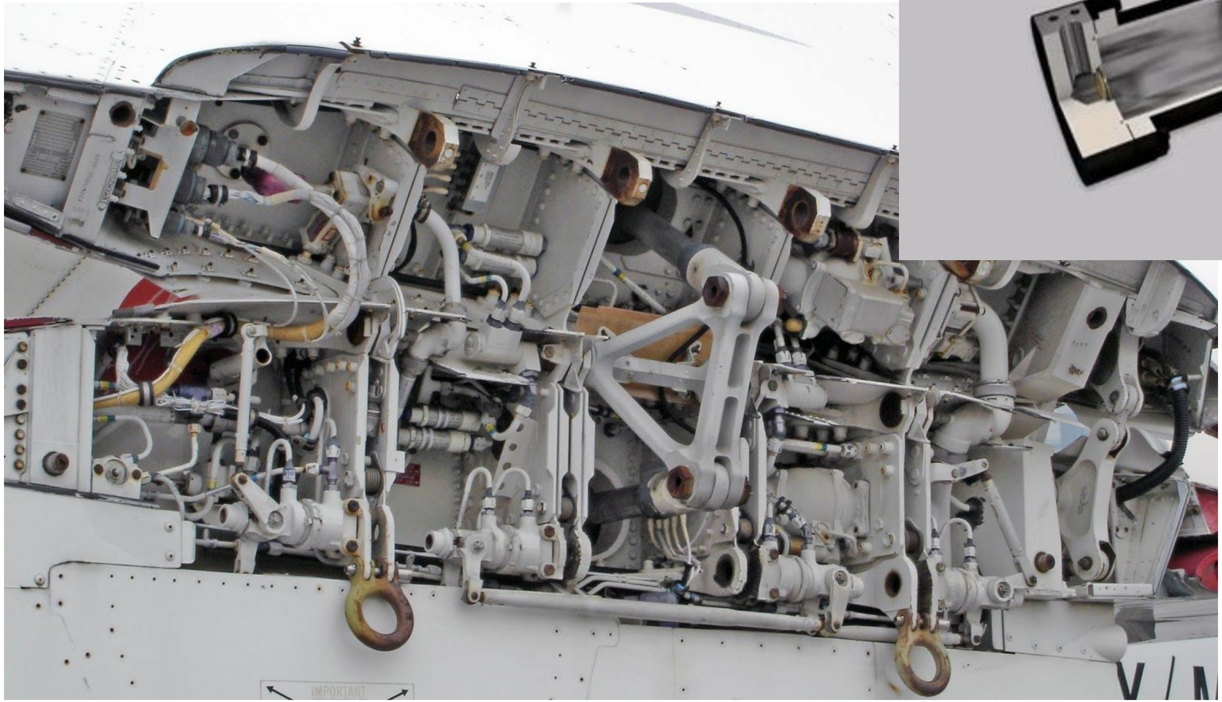


Linkages in real life

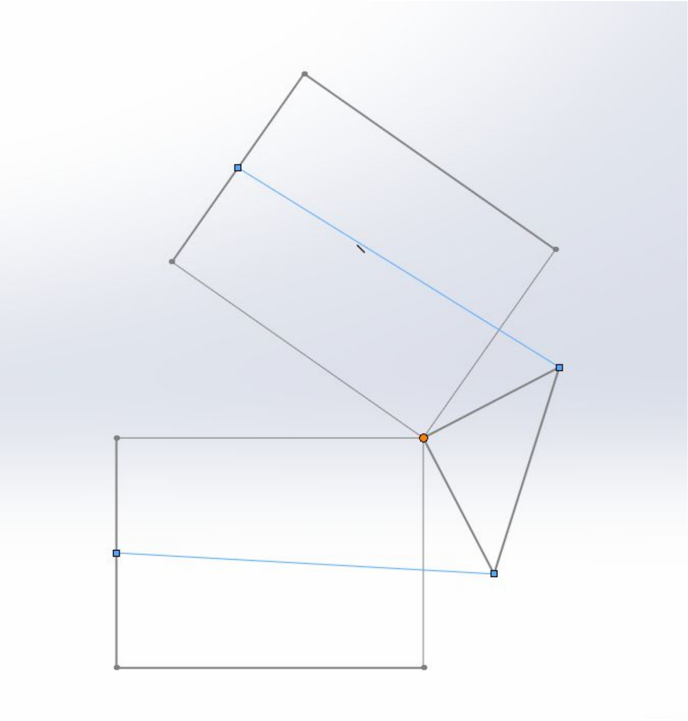
The A-6 Intruder is a US military jet that is designed to fit on aircraft carriers..

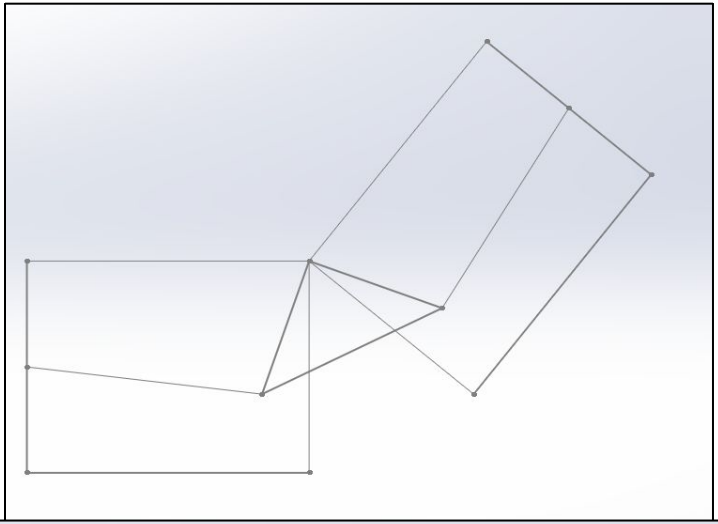
Linkages in real life

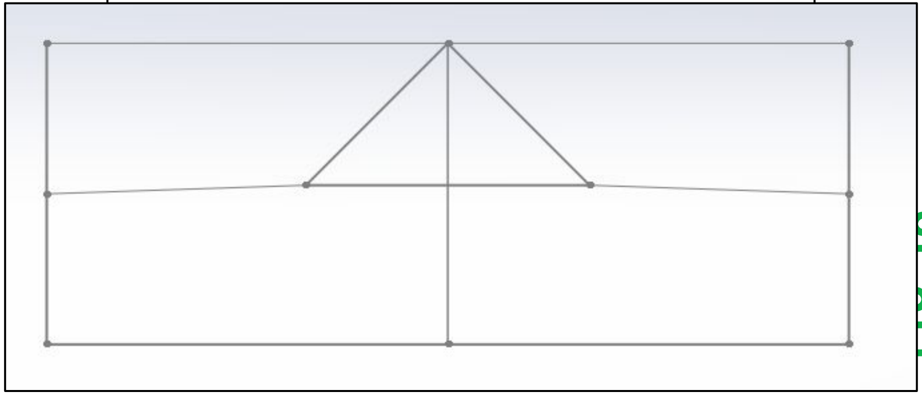
How do they do this?



Modeling linkages







Cantilevers vs Simply Supported Beams

- Forces are much higher in cantilevers: avoid when possible!
- This goes for axles as well- cantilever wheeled drivebases like WCD are very easy to underdesign!

I could do the math, but the maximum stress on a cantilevered beam is <u>much</u> higher than a similar situation that is simply supported

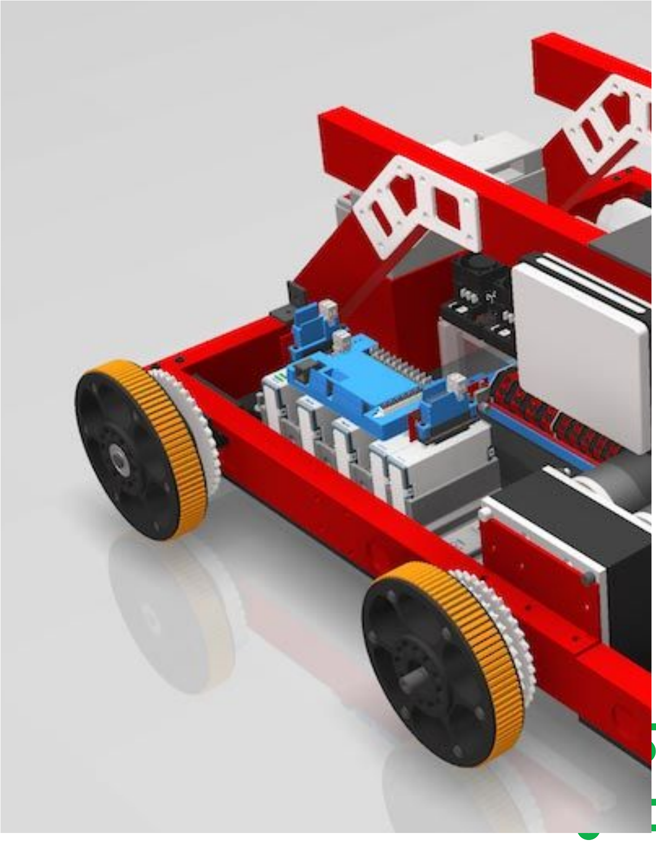
Cantilevers in FIRST

These wheels are supported via cantilever...

To design, one must consider:

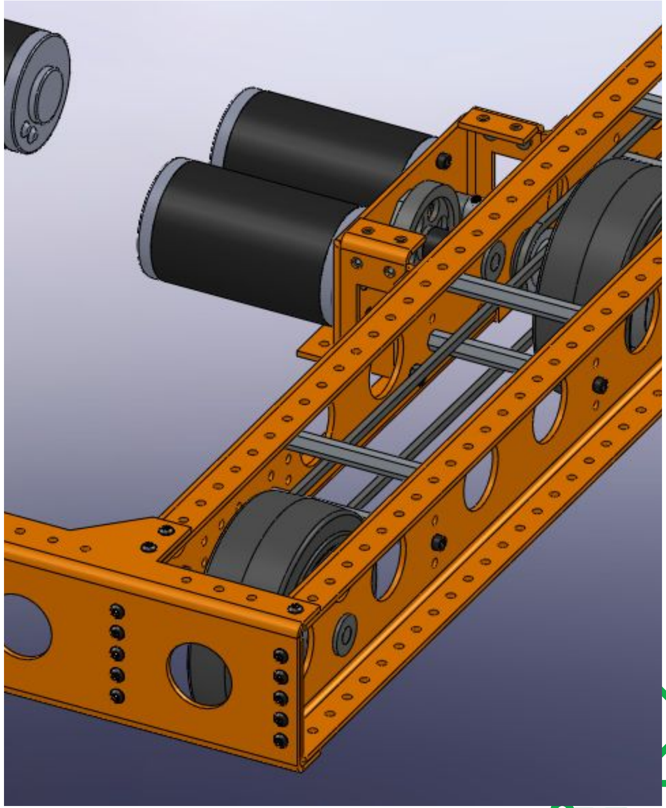
- Distance from wheeler to support (moments are affected just by geometry)
- Support of the axle in the robot (bearing types + location + mounting)

Very easy to mess up...



...vs. simply supported

- Forces on axle, supports, etc. is **much** lower
- Don't have to think as much about forces.. most parts will be able to withstand the forces that this drivebase would encounter and then some



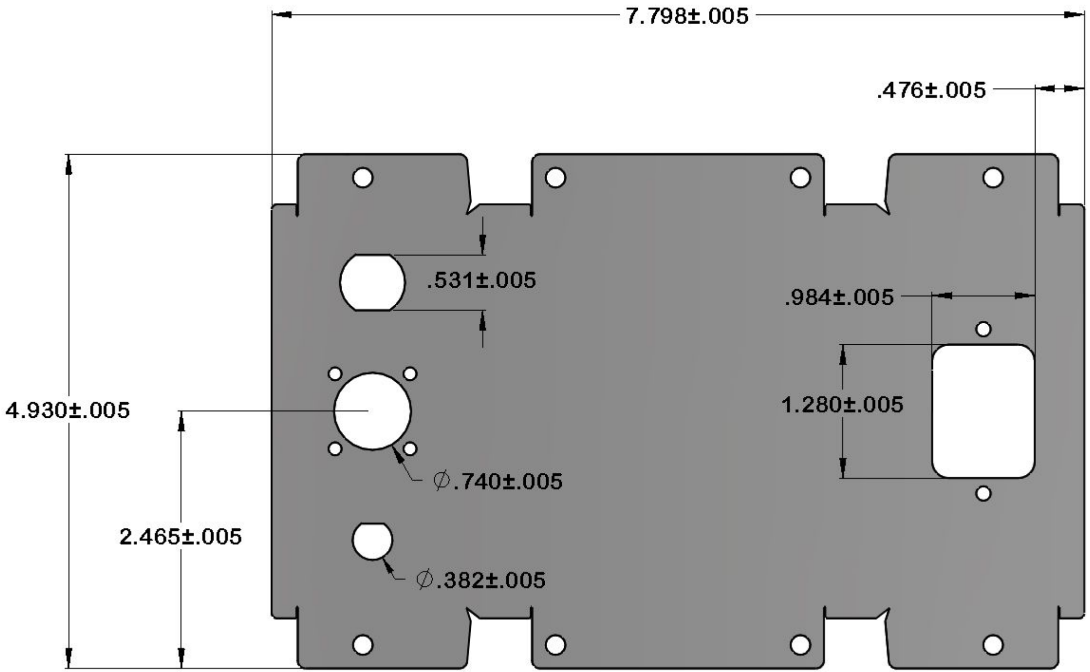
Tolerances

- Nothing is perfect.. including our machining processes. There is error associated with them.
- How do we deal with that? Enter tolerances.
    - Def: a maximum deviation allowed from a nominal (written) value
- Ex: You want a axle cut to 5”. However, your machinist can’t get something to *exactly* 5”, so you say 5” +/- 0.005”.. Now he has a range to work with!

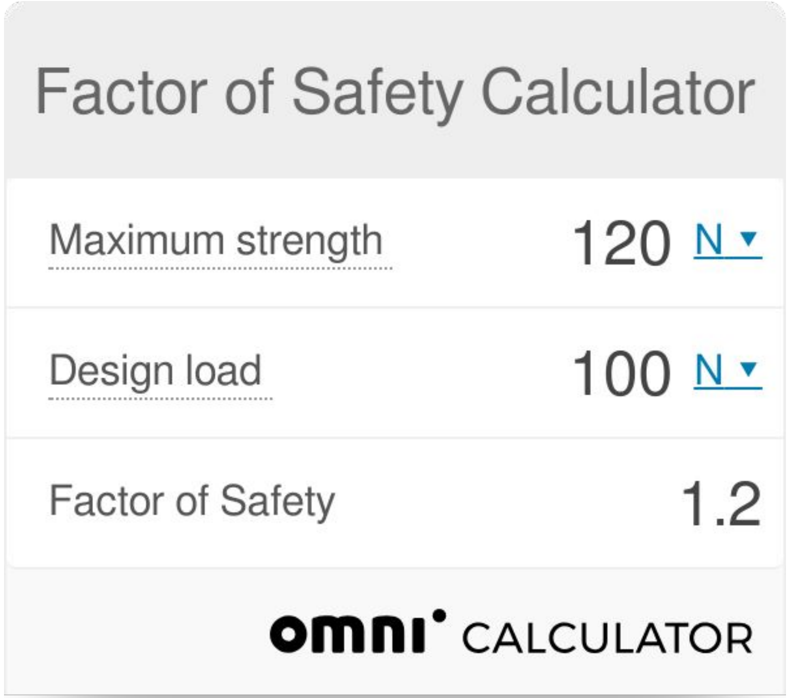
TLDR: Tolerances are something to think about when selecting both materials and manufacturing processes!

Tolerance in CAD

You can specify this in CAD when making drawings.. This practice is called **geometric dimensioning and tolerancing** (GD&T)



Always Include a Safety Factor



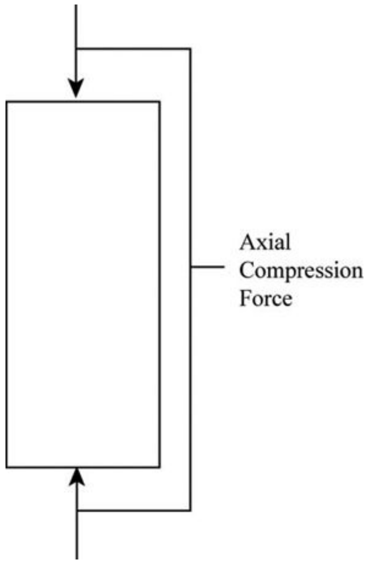
Def. Bods for Robotics

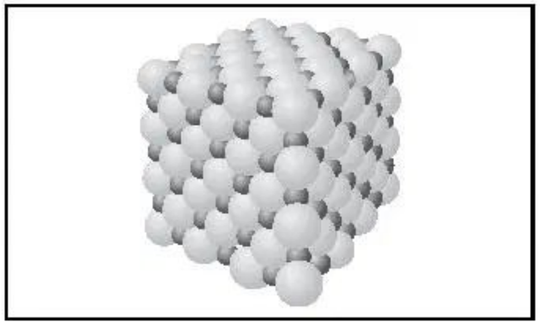
What is a def bod?

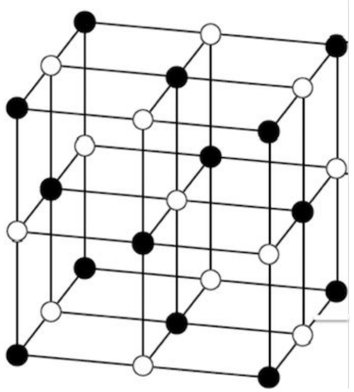
- **Def**ormable **bod**y
- Engineering materials are all squishy like springs!
- Help us understand **why things break**

Material Science Basics

- We can relate the forces we apply at a big level to things that happen at the molecular level

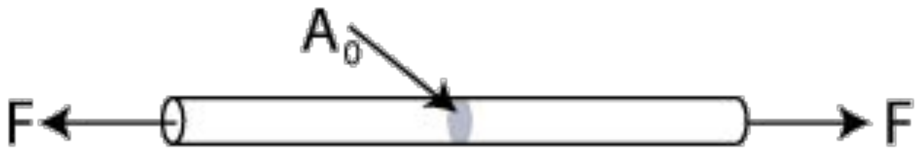






Stresses and Strains

- Big things are stronger.. We know this! But we need a way to see how much a force affects a designed part.
- Enter **stress**! Consider it a force applied over an area (aka pressure). Measured in psi/Pa
- **Strain** tells us how much a material deforms from an applied stress (think back to the crystal structures and how they stretch out!) Measured in % change



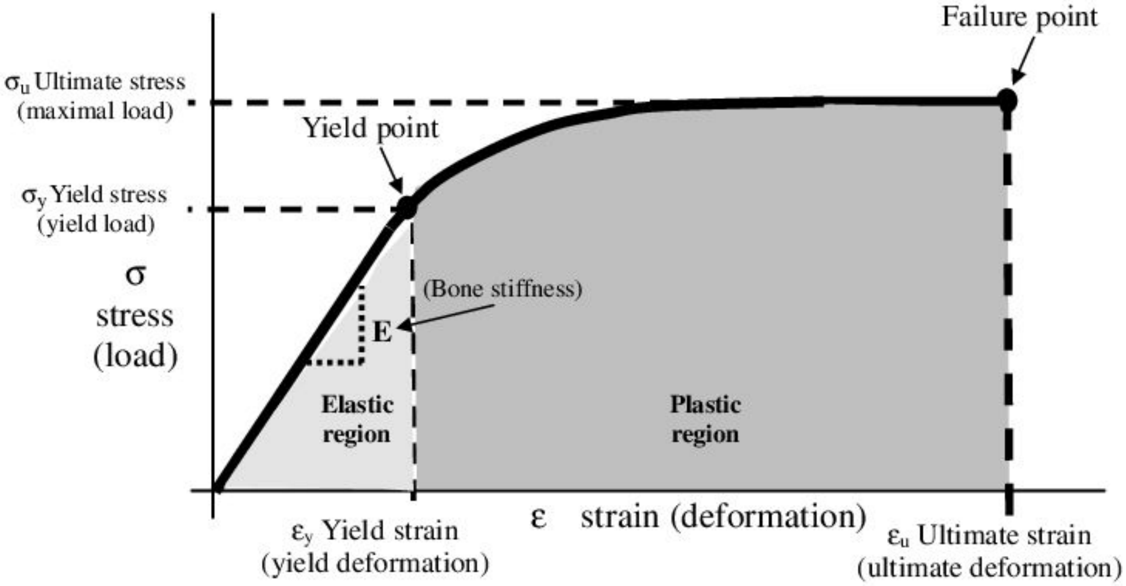
$$\text{Stress, } \sigma = \frac{\text{Force}}{\text{Cross-Sectional Area}} = \frac{F}{A_0}$$

Relating Stresses and Strains

- Stresses and strains are related and this is shown through a **stress-strain diagram**. These diagrams are unique to every material, but there are some similarities.

Concepts:

- Elastic vs. Plastic Deformation
- Yield stress
- Young's Modulus
- Strain hardening



Yield Strength

Listed as a material property, such as this spec sheet for 6061 Aluminum from McMaster Carr:

Multipurpose 6061 Aluminum Sheets and Bars with Certification

All of these sheets and bars come with a traceable lot number and test report. The most widely used aluminum, 6061 is fabricated into everything from pipe fittings and containers to automotive and aerospace parts. It is strong and corrosion resistant, plus it's easy to machine and weld.

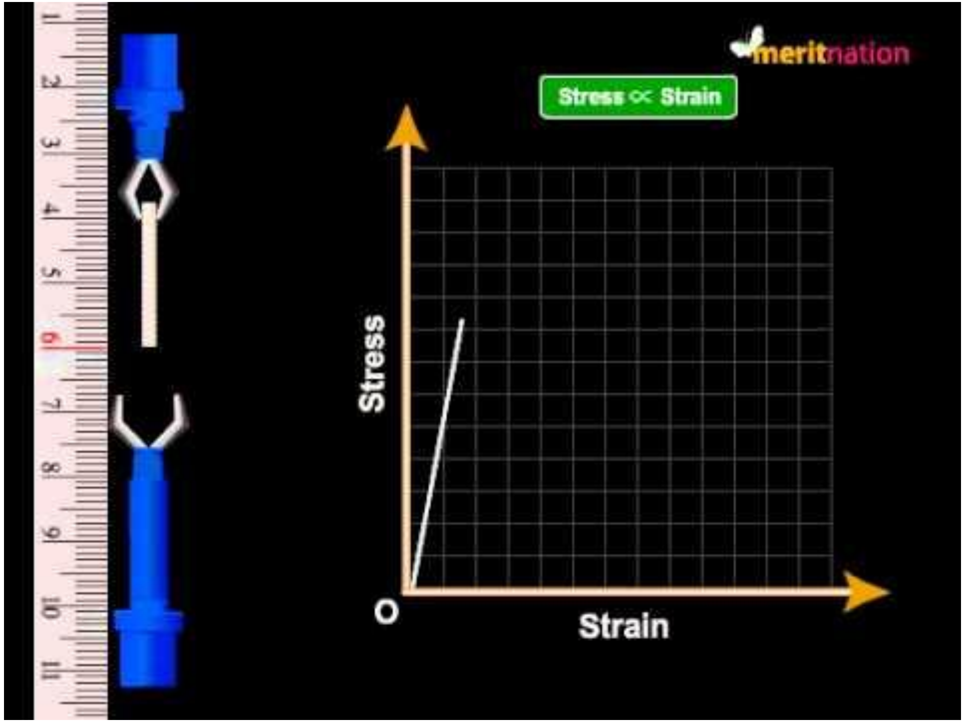
Cold-rolled sheets are cut from large pieces to the widths and lengths listed, so the edges may not be parallel.

Extruded sheets and **bars** are formed by a die for close-tolerance widths, then cut to the lengths listed.

Sheets

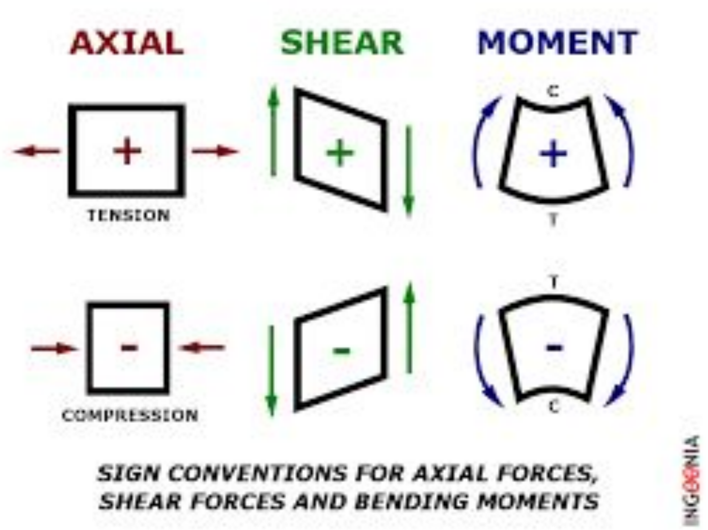
- Yield Strength: 35,000 psi
- Hardness: See table
- Temper:
  Cold Rolled: T6
  Extruded: T6511
- Fabrication: See table
- Specifications Met:
  Cold Rolled: AMS 4027, ASTM B209
  Extruded: ASTM B221

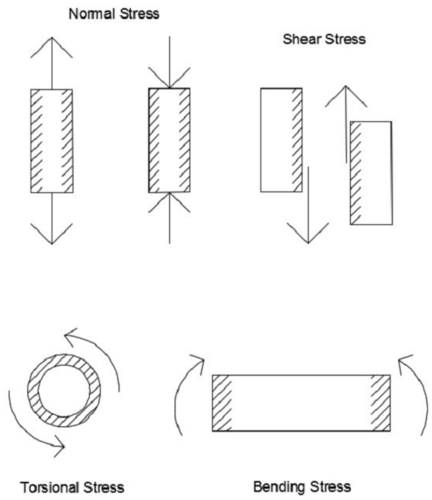
A quick demo...



Stress Types

You might encounter a few different types of stresses when analyzing your robot:

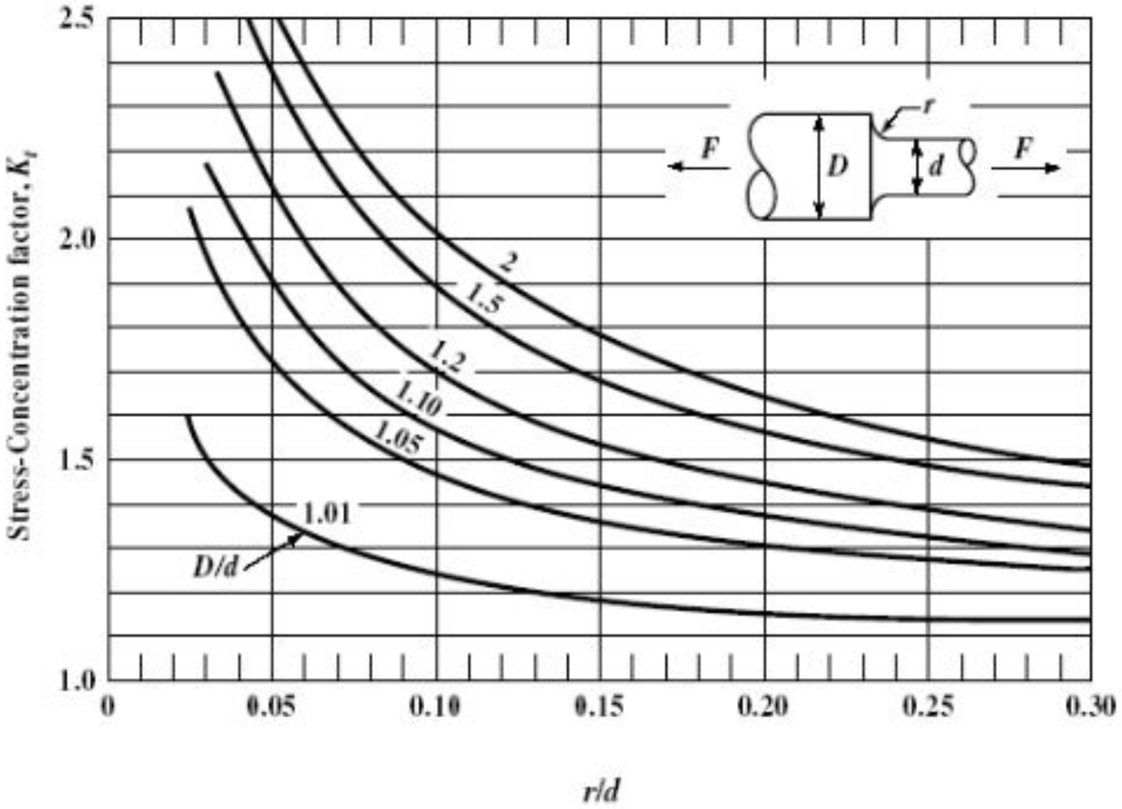




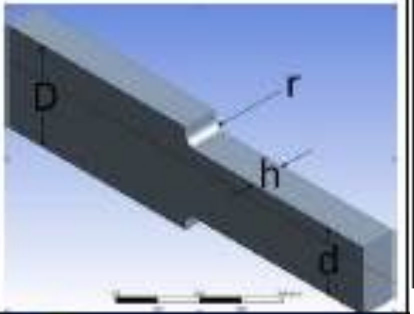
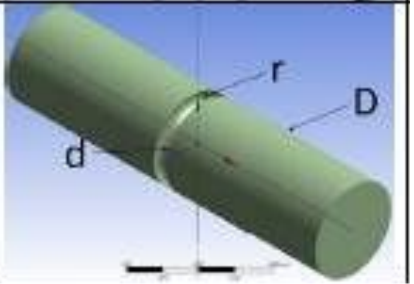
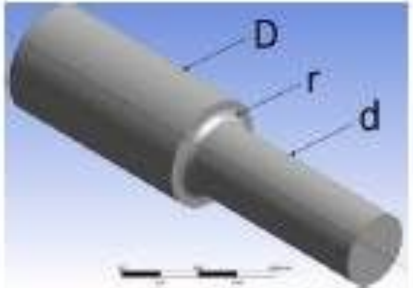
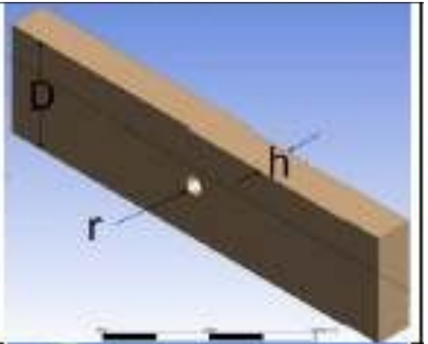
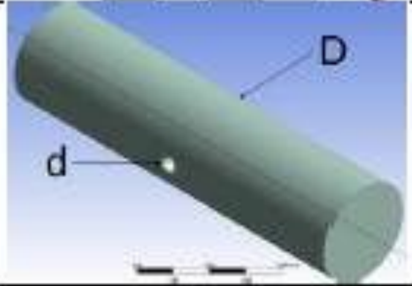
While it’s actually pretty complicated to do the math, knowing these is useful!

Stress Concentrations

- Sometimes, geometry can cause stress in a part to build at certain points…
- This is called a stress concentration! The local stresses can be 3-10x higher than what you'd expect.. **Just based on geometry.**



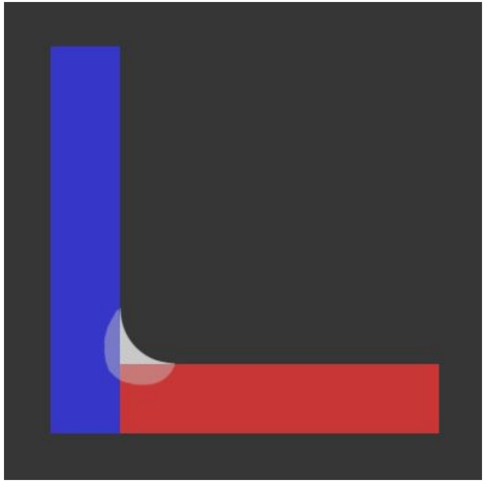
Geometry that causes SCs..

Graded Plate	
Grooved Shaft	
Graded Shaft	
Perforated Plate	
Perforated Shaft	

A bit of a real world example..

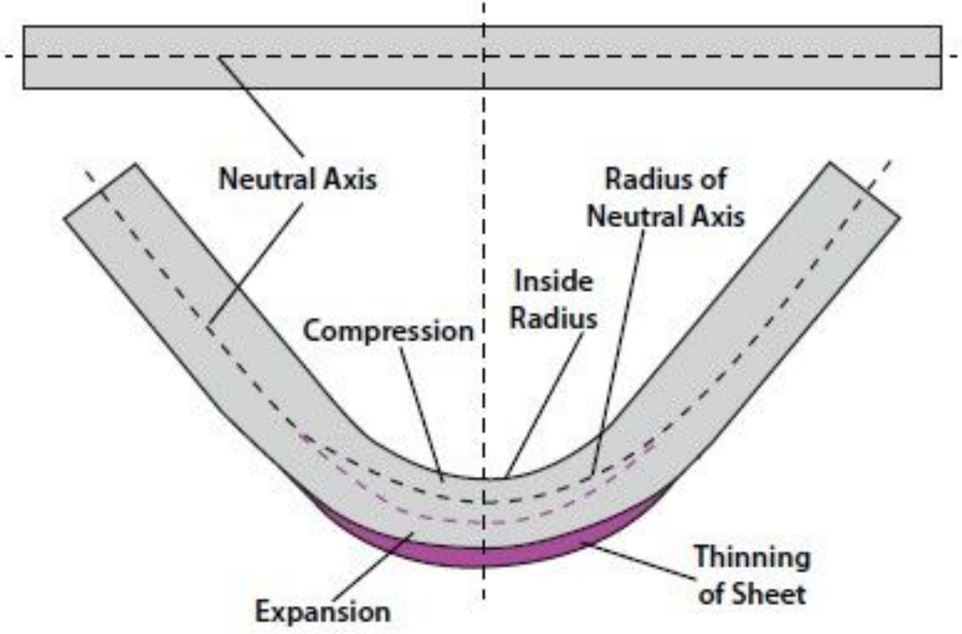
Fillets

- Fillets are rounded corners! Can be interior or exterior
- Fillets can help relieve stress concentrations & make parts easier to manufacture (waterjets like them better for sure)
- **Tldr: use fillets when designing, squared corners = bad**



A bit more on bending..

Bending moments cause both axial tension (expansion) and compression:



How to reduce bending

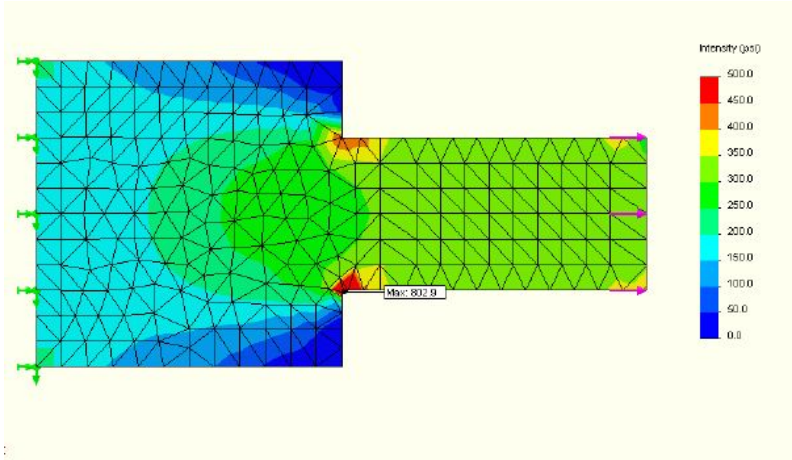
- If something is bending, add more material where it counts.. The ends farthest from the neutral axis!
- This is the most effective way to increase a part’s **moment of inertia**

So what?

Well.. if this happened to your robot... wouldn't you want to know the science behind why so you can make sure it doesn't happen again?

Simulation

- CAD programs often have built-in simulation tools that let you test your designs (FEA- finite element analysis)
- How does this work?
  - 1. Take your solid model
  - 2. Mesh it
  - 3. Computer numerically solves forces inside
- What does this mean?
  - HARD to get physically accurate results!
  - Most FEA is checked against hand-calculations



Advanced (Math-y) Things

Using Static FBDs for design

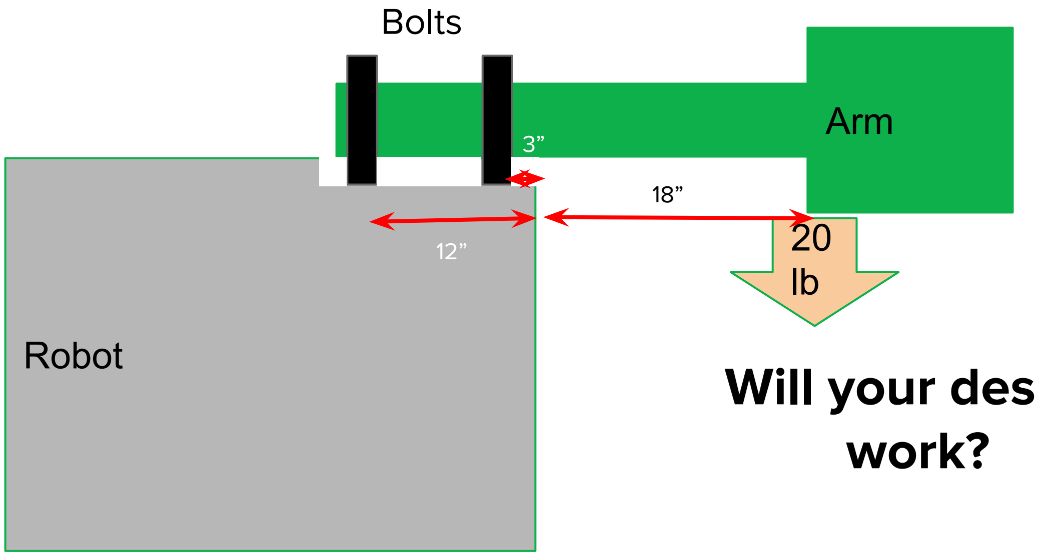
- Figuring out the forces when nothing is moving is incredibly useful (in engineering we call this statics)

In statics:

1. The sum of all forces in all directions must equal 0: $\sum F=0$
2. The sum of all moments (using the same point) must equal 0: $\sum M=0$

Using Static FBDs for design

You’re trying to design an 20 lb. arm for your robot and you want to know if two bolts in the following configuration will work. You know the bolts can support a load of 50 lbs each from the spec sheet.

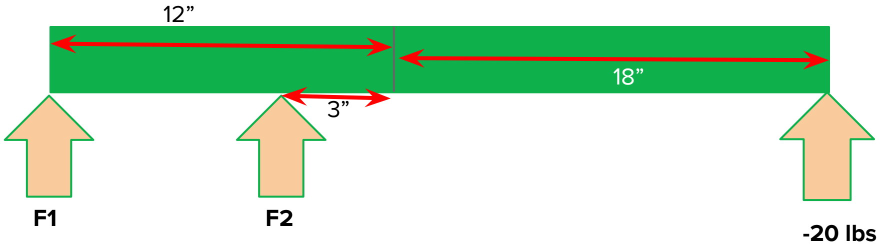


Will your design work?

Using Static FBDs for Design

but zach! why -20 lbs upwards?

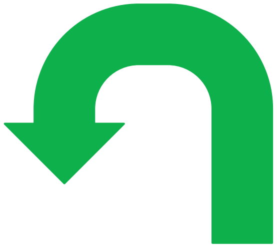
Simplify problem to:



Summing up forces and moments and solving equations:

∑F = 0 = F1 + F2 + (-20 lbs)

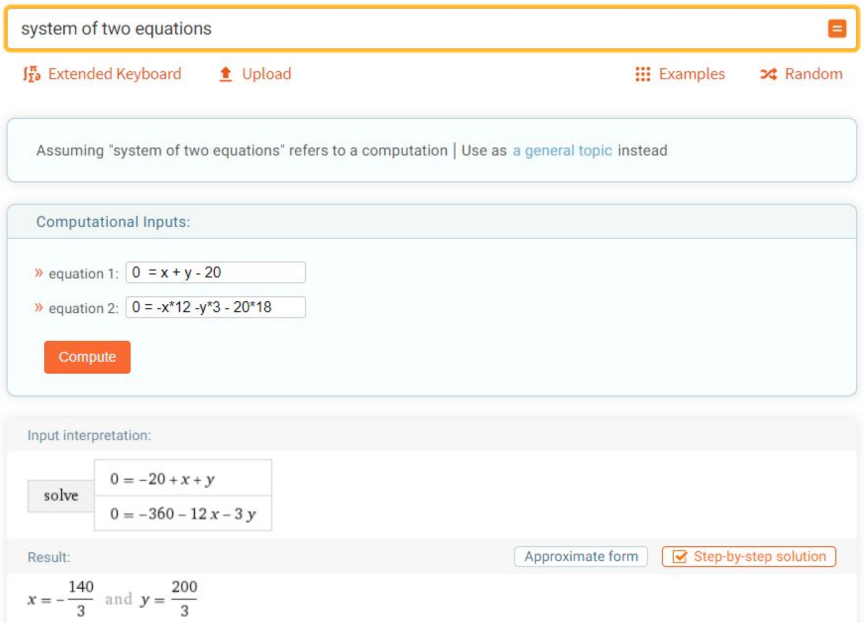
∑M = 0 = - (F1*12”) - (F2*3”) + (-20 lbs*18”)



Remember right hand rule!

Solving Equations

If you’re lazy like me, check out wolframalpha.com



x = F1 = -140/3 lbs = 46.67 lbs downwards

y = F2 = 200/3 lbs = 66.67 lbs upwards

Checking:

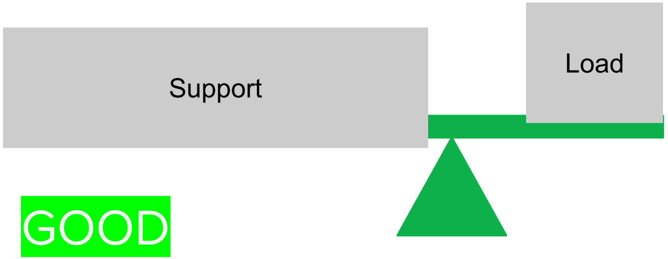
(-46.67 lbs) + (66.67 lbs) + (-20 lbs) = 0

-(-46.67 lbs *12”) - (66.67 lbs*3”) + (-20 lbs*18”) = 0

Static FBDs for Design

- From this analysis, we can see that the second bolt will fail- it is over the limit
  - Note that this case is a simplification of actually how to do static analysis.. Still good though :)

TLDR: Cantilever structures are essentially big levers! Levers can multiply forces… need to account for this in design:



Real World Examples

FRC 360 Arm

Their lifting mechanism broke off the robot.

Like the previous example, it wasn't attached in a way that would support the load.